Strongly enhanced inelastic collisions in a Bose–Einstein condensate near Feshbach resonances

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The properties of Bose–Einstein condensed gases can be strongly altered by tuning the external magnetic field near a Feshbach resonance. Feshbach resonances affect elastic collisions and lead to the observed modification of the scattering length. However, as we report here, this is accompanied by a strong increase in the rate of inelastic collisions. The observed three–body loss rate in a sodium Bose–Einstein condensate increased when the scattering length was tuned to both larger or smaller values than the off–resonant value. This observation and the maximum measured increase of the loss rate by several orders of magnitude are not accounted for by theoretical treatments. The strong losses impose severe limitations for using Feshbach resonances to tune the properties of Bose–Einstein condensates. A new Feshbach resonance in sodium at 1195 G was observed.

Most of the properties of Bose–Einstein condensates in dilute alkali gases are dominated by two–body collisions, which can be characterized by the s–wave scattering length a. The sign and the absolute value of the scattering length determine e.g. stability, internal energy, formation rate, size, and collective excitations of a condensate. Near a Feshbach resonance the scattering length varies dispersively [1, 2] covering the whole range of positive and negative values. Thus it should be possible to study strongly interacting, weakly or non interacting, or collapsing condensates [3] all with the same alkali species and experimental setup.

A Feshbach resonance occurs when the energy of a molecular (quasi–) bound state is tuned to the energy of two colliding atoms by applying an external magnetic field. Such resonances have been observed in a Bose–Einstein condensate of $\mathrm{Na}(F=1, m_F=+1)$ atoms at 853 G and 907 G [4, 5], and in two experiments with cold clouds of $^{85}\mathrm{Rb}(F=2, m_F=-2)$ atoms at 164 G [6]. In the sodium experiment, the scattering length a was observed to vary dispersively as a function of the magnetic field B, in agreement with the theoretical prediction [2]:

$$a = a_0\left(1 + \frac{\Delta}{B_0 - B}\right), \tag{1}$$

where a_0 is the off–resonant scattering length, and Δ characterizes the width of the resonance.

In this Letter we report on the observation of a broad Feshbach resonance in sodium in the $F = 1, m_F = -1$ state at 1195 G, and we investigate the strong inelastic processes accompanying all three sodium resonances, which result in a rapid loss of atoms while approaching or crossing the resonances with the external magnetic field. The losses show an unpredicted dependence on the external magnetic field and impose strong constraints on future experiments exploiting the tunability of the scattering length.

The experimental set–up is very similar to that described in [4]. Magnetically trapped condensates in the $F = 1, m_F = -1$ state were transferred into an optical trap consisting of a focused far off–resonant infrared laser beam [7]. The atoms could be transferred to the $m_F = +1$ state by an rf–pulse in a 1 G bias field. For the studies of the Feshbach resonances, bias fields of up to 1500 G were applied with ramp speeds of up to 1000 G/ms. Inhomogenities in the bias field exerted a force mainly in the axial direction. To prevent atoms from escaping, green light from an argon–ion laser was focused into two light sheets at the ends of the cigar shaped condensates, forming repulsive light barriers. The resulting trapping frequencies were around 1500 Hz radially and 150 Hz axially. The trap losses were studied by ramping the bias field with different ramp speeds to various field values near the resonances. The atoms were probed in ballistic expansion after suddenly switching off the optical trap. The magnetic field was switched off 2 ms later to ensure that the high field value of the scattering length was responsible for the acceleration of the atoms. After 7 – 25 ms free expansion the atoms were optically pumped into the $F = 2$ state and observed in absorption using the cycling transition in a small bias field of 0.5 G.

The number of atoms N, the scattering length a and the mean density $\langle n \rangle$ could be obtained from the absorption images. N is calculated from the integrated optical density. The mean field energy $2\pi\hbar^2 a \langle n \rangle / m$ is converted into kinetic energy $mv_{rms}^2/2$ after switching off the trap. The root–mean–square velocity v_{rms}^2 can be extracted from the size of the cloud after the time of flight. As discussed in Ref. [4], the mean density $\langle n \rangle$ is proportional to $N(Na)^{-3/5}$ for a three–dimensional harmonic oscillator potential, and thus the scattering length a scales as

$$a \sim \frac{v_{rms}^5}{N}. \tag{2}$$

Normalized to unity far away from the resonance, v_{rms}^5/N is equal to a/a_0. The proportionality factor in eqn.(2) involves the mean trapping frequency which was not accurately measured. However, we can obtain absolute values by multiplying the normalized scattering length with the theoretical value of a_0. The off–resonance scattering length $a_0 = 2.75\,\mathrm{nm}$ of sodium at zero field increases to the triplet scattering length $a_0 = a_T = 3.3\,\mathrm{nm}$ [8] at the high fields of the resonances. Using this value, the mean density is obtained from the root–mean–square velocity,

$$\langle n \rangle = \frac{m^2 v_{rms}^2}{4\pi\hbar^2 a}. \tag{3}$$

The peak density n_0 is given by $n_0 = (7/4)\langle n \rangle$ in a parabolic potential.

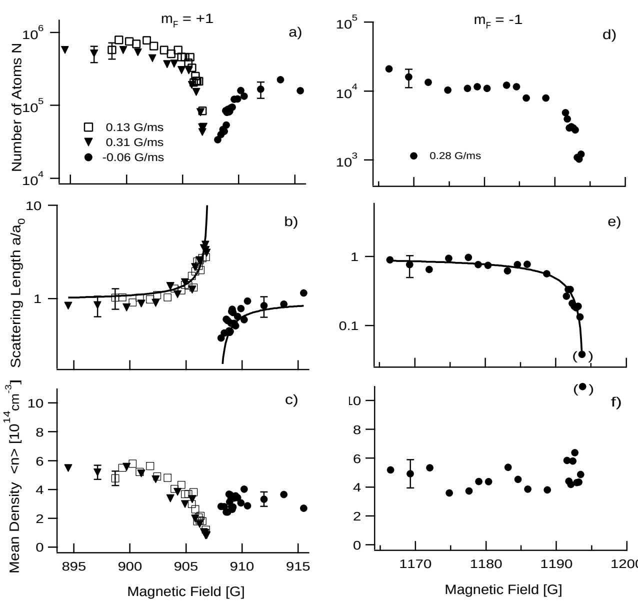

Figure 1: Number of atoms N, normalized scattering length a/a_0 and mean density $\langle n \rangle$ versus the magnetic field near the 907 G and 1195 G Feshbach resonances. The different symbols for the data near the 907 G resonance correspond to different ramp speeds of the magnetic field. All data were extracted from time–of–flight images. The errors due to background noise of the images, thermal atoms, and loading fluctuations of the optical trap are indicated by single error bars in each curve.

The experimental results for the 907 G and 1195 G resonances are shown in Fig. 1. The number of atoms, the normalized scattering length and the density are plotted versus the magnetic field. The resonances can be identified by enhanced losses. The 907 G resonance could be approached from higher field values by crossing it first with very high ramp speed. This was not possible for the 1195 G resonance due to strong losses, and also not for the 853 G resonance due to its proximity to the 907 G resonance and the technical difficulty of suddenly reversing the magnetic field ramp. For the 907 G resonance the dispersive change in a can clearly be identified. The solid lines correspond to the predicted shapes with width parameters $\Delta = 1$ G in Fig. (b), and $\Delta = -4$ G in Fig. (e). The negative width parameter for the 1195 G resonance reflects the decreasing scattering length when the resonance is approached from the low field side. The uncertainties of the positions are mainly due to uncertainties of the magnetic field calibration.

The time dependent loss of atoms from the condensate can be parameterized as

$$\frac{\dot{N}}{N} = -\sum_i K_i \, \langle n^{i-1} \rangle, \tag{4}$$

where K_i denotes an i–body loss coefficient, and $\langle n \rangle$ the spatially averaged density. In general, the density n depends on the number of atoms N in the trap, and the loss curve is non–exponential. One–body losses, e.g. due to background gas collisions or spontaneous light scattering, are negligible under our experimental conditions. An increase of the dipolar relaxation rate (two–body collisions) near Feshbach resonances has been predicted [1]. However, for sodium in the lowest energy hyperfine state $F = 1, m_F = +1$ binary inelastic collisions are not possible. Collisions involving more than three atoms are not expected to contribute. Thus the experimental study of the loss processes focuses on the three–body losses around the $F = 1, m_F = +1$ resonances, while both two– and three–body losses must be considered for the $F = 1, m_F = -1$ resonance.

Figs. 1 (c) and (f) show a decreasing or nearly constant density when the resonances were approached. Thus the enhanced trap losses can only be explained with increasing coefficients for the inelastic processes. The quantity $\dot{N}/N\langle n^2 \rangle$ is plotted versus the magnetic field in Fig. 2 for both the 907 G and the 1195 G resonances. Assuming that mainly three–body collisions cause the trap losses, these plots correspond to the coefficient K_3. For the 907 G (1195 G) resonance, the off–resonant value of $\dot{N}/N\langle n^2 \rangle$ is about 20 (60) times larger than the value for K_3 measured at low fields [7]. Close to the resonances, the loss coefficient strongly increases both when tuning the scattering length larger or smaller than the off–resonant value. Since the density is nearly constant near the 1195 G resonance, the data can also be interpreted by a two–body coefficient $K_2 = \dot{N}/N\langle n \rangle$ with an off–resonant value of about $30 \times 10^{-15}\,\mathrm{cm}^3/\mathrm{s}$, increasing by a factor of more than 50 near the resonance. The contribution of the two processes cannot be distinguished by our data. However, dipolar losses are much better understood than three–body losses. The off–resonant value of K_2 is expected to be about $10^{-15}\,\mathrm{cm}^3/\mathrm{s}$ [9] in the magnetic field range around

the Feshbach resonances, suggesting that the three–body collisions are the dominant loss mechanism also for the 1195 G resonance.

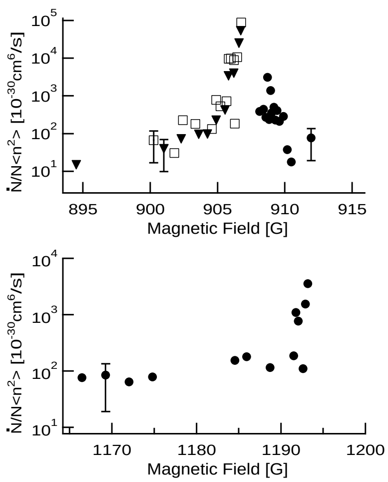

Figure 2: Rate coefficients for inelastic collisions near Feshbach resonances. $\dot{N}/N\langle n^2\rangle$ is plotted versus the magnetic field. The time derivative $\dot{N}$ was calculated from neighboring points without smoothing the data.

The data analysis following eqns.(2) and (3) is based on two major assumptions: the Thomas–Fermi approximation in which the kinetic energy is small compared to the mean–field energy, and the assumption that the atoms maintain the equilibrium density distribution during the change of the scattering length. The Thomas–Fermi approximation is well justified for all data points with $a/a_0 > 1$. For $a/a_0 < 1$ close to the resonances, the mean field energy of the condensates is only a few times larger than the level spacing in the trap. This leads to an overestimate of the density and thus to an underestimate of K_3 for the data points with smallest scattering length. The ramp speeds of the magnetic field were chosen low enough to ensure adiabaticity, characterized by the condition $\dot{a}/a \ll \omega_i$ [3], where $\omega_i = 2\pi\nu_i$ are the trapping frequencies. Only for the data point closest to the 1195 G resonance (in parentheses) this condition is not fulfilled. Indeed, the scattering length a/a_0 (Fig. 1b) and the quantity $\dot{N}/N\langle n^2\rangle$ (Fig. 2a) are independent of the ramp speeds, supporting the assumption of adiabaticity.

The observed increase and the magnetic field dependence of the three-body collision rate is not accounted for by any theory. Two theoretical treatments suggested that the rate coefficient K_3 should vary monotonically with the scattering length following some power law. Fedichev et al. [10] derived the universal relation $K_3 = 3.9\hbar a^4/2m$. This prediction was in fairly good agreement with measurements in rubidium [11] and sodium [7] in low magnetic fields, even though it is not clear that the assumptions are valid in these experiments. By considering the breakup of a dimer by a third atom as the inverse process of recombination, Moerdijk et al. [12] suggested that the recombination rate is proportional to a^2. Although the assumptions of those theories might not be fulfilled near Feshbach resonances, they raised the hope that loss rates should not increase in the region of the Feshbach resonance where the scattering length is small. However, for scattering lengths smaller than a_0 a substantial increase of the coefficient K_3 was observed. Thus, these measurements show the need for a more accurate theoretical treatment of ultracold three–body collisions.

Another way to characterize the losses is a rapid sweep across the resonances. We determined the fraction of atoms which were lost in sweeping through the 853 G resonance and the 907 G resonance at different ramping speeds [13]. For this, the optical trap and the magnetic field were suddenly switched off, either before or after crossing the resonance, and the number of atoms was determined from absorption images as before.

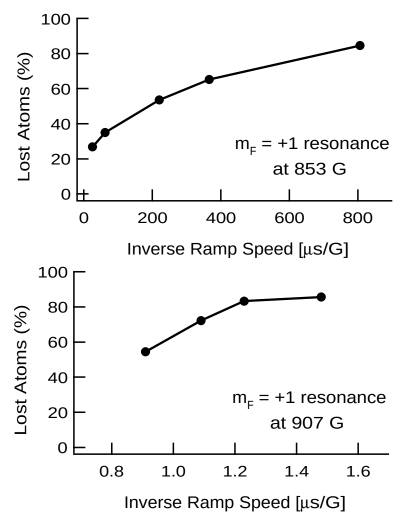

Figure 3: Fraction of lost atoms after crossing the Feshbach resonances at 853 G and 907 G for different inverse ramp speeds of the magnetic field.

Fig. 3 shows the fraction of lost atoms as a function of the inverse ramp speed. Using the width of 1 G for the 907 G resonance, this implies that 70 % of all atoms are lost in one microsecond. Across the 853 G resonance 70 % of all atoms are lost at a ramp speed of $1\,\mathrm{G}/400\,\mu\mathrm{s}$. Assuming a universal behavior near Feshbach resonances, this implies that the strength of the 853 G resonance is four hundred times weaker than of the 907 G resonance. Since the width Δ of the Feshbach resonance is proportional to the coupling strength between the two involved molecular states [2], a width of 0.0025 G for the 853 G resonance is estimated. A theoretical prediction for the widths of the 907 G and the 853 G resonances are 1 G

and 0.01 G, respectively [14].

The loss of 70 % of the atoms in only one microsecond cannot be explained by the usual picture of inelastic collisions. Due to the very small kinetic energy of Bose–Einstein–condensed atoms, which is of order $\frac{\hbar^2}{2m}(\frac{n}{N})^{2/3}$ [15], the travel distance of an atom in 1 μs is less than 1 nm under our conditions, much smaller than the mean distance between the atoms, $d \approx n^{-1/3} \approx 100$ nm. Loss by two– or three–body collisions should then be limited to the small fraction of atoms which happens to be very close to other atoms. Possible explanations for the observed large losses are the divergence of the scattering length which allows for extremely long–range interactions between atoms, the formation of a molecular condensate, as recently proposed [16], or the impulsive excitation of solitons [17] when the region of negative scattering length is crossed. All suggested explanations require new concepts in many–body theory.

In conclusion, we have reported on the observation of a new, $F = 1, m_F = -1$ Feshbach resonance at 1195 G in sodium, and we have investigated the enhanced trap losses accompanying all three resonances observed so far. The scattering length could be altered in the range of $0.2 \leq a/a_0 \leq 5$. The three–body loss coefficient K_3 increased for both larger and smaller scattering length by up to more than three orders of magnitude. Those losses show that the density of the sodium samples must be reduced well below $10^{14}\,\mathrm{cm}^{-3}$ for further studies exploiting the tunability of the scattering length near Feshbach resonances.

Our sweep experiments revealed that approaching a Feshbach resonance from the high magnetic field side is strongly affected by trap loss while crossing the resonance. The new $m_F = -1$ resonance at 1195 G is well suited for studies of Bose–Einstein condensates with zero or negative scattering length, since this region is on the low field side of the resonance and can be directly approached without crossing any resonance.

So far, the physics of gaseous Bose-Einstein condensates has been very well described including only binary interactions between the atoms [15]. Feshbach resonances might open the possibility to study physics beyond this approximation which breaks down when the scattering length diverges, and also for very small scattering lengths when one has to consider higher order terms in the atomic interactions. Feshbach resonances may also lead to new inelastic processes. The observed losses of atoms near Feshbach resonances indicate molecular and many-body physics which is not yet accounted for by any theory.

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